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Comput. Methods Appl. Mech. Engrg. 299 (2016) 421–439

Computer methods in applied mechanics and engineering

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Electrostatic–viscoelastic finite element model of dielectric actuators

T. Schlögl*, S. Leyendecker

Chair of Applied Dynamics, University of Erlangen-Nuremberg, Haberstr. 1, 91058 Erlangen, Germany

Received 20 April 2015; received in revised form 8 October 2015; accepted 15 October 2015
Available online 1 November 2015

Abstract

The aim of this work is to set up a numerical framework to characterise the deformation process and effective forces when voltage is applied to dielectric elastomer actuators. Based on an existing model for non-linear electro-elasticity that covers the static case only, inertia terms are included in order to obtain a description of the deformation process depending on time. A potential energy function that is composed of Neo-Hooke material behaviour, electric field energy and coupling terms covers the material properties. Combined with the kinetic energy, a Lagrange function forms the basis in a variational setting of the model. Viscoelastic effects are included using non-conservative forces and account for time dependent strains. The action is approximated using quadrature rules and discretising with finite elements in space. A discrete version of Hamilton's principle leads to a structure preserving integration scheme for DEAs. The integration scheme is implemented as C++ code and applied to various examples.

Keywords: Dielectric elastomer; Electroactive polymer; Finite element model; Viscoelastic; Electrostatic; Hyperelastic

1. Introduction

Modern robotic systems still suffer some severe limitations with regard to their efficiency concerning energy and resources. Due to the high weight of electrical drives and portable batteries, they are far from being autarkic for longer times. Furthermore, the rigid coupling between electrical drives and joints does not allow for dynamic motions like they occur in nature, where flexible muscles act as an energy buffer. Due to their potential capability of solving some of these problems, dielectric elastomer actuators (DEAs, also called artificial muscles) are the subject of intense research [1–7]. As with capacitors, when an external voltage is applied to the conductive layers, an electric field is established. Resulting electrostatic stresses lead to a contraction of the DEA, as illustrated in Fig. 1.

Within the collaborative research project Bionicum,[1] the use of artificial muscles is investigated. At the Institute for Factory Automation and Production Systems (FAPS) in Erlangen, Germany, the development of the automated production of multilayer DEAs together with lightweight power electronics is explored. A numerical framework to characterise the deformation process and effective forces is derived at the Chair of Applied Dynamics (LTD) in

* Corresponding author.
E-mail address: tristan.schloegl@fau.de (T. Schlögl).

1 see http://www.bionicum.de/forschung/projekte/muskeln/.

http://dx.doi.org/10.1016/j.cma.2015.10.017

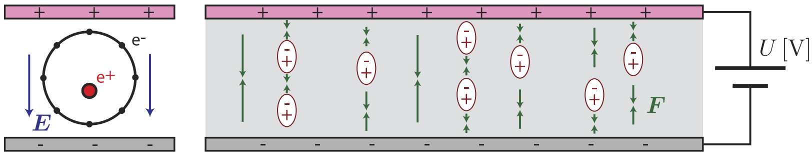

Fig. 1. Functional principle of a dielectric elastomer actuator.

Erlangen, Germany. This model is necessary to understand and to predict the behaviour when voltage is applied to the DEA and to efficiently control the muscles.

In electronics, electrostriction generally describes the deformation of a dielectric material caused by an electric field, due to the interaction between charges [8]. Considering the sandwich structure of a DEA, charges can be found on the electrodes as free charges and in form of polarisation within the elastomer as bound charges. In 1998, using a simplified one-dimensional model, Pelrine et al. show that for incompressible elastomers, the resulting electrostatic pressure is twice the pressure present in a rigid plate capacitor [5]. It is stated that the additional forces arise because like charges on the electrodes repel each other. However, when applying the principle of virtual work, Pelrine implicitly assumes that all forces act perpendicular to the capacitor plates, leading to a one-dimensional model. Due to its simplicity, the derived scalar formula

$$p = \varepsilon_0 \varepsilon_r E^2 \tag{1}$$

for the effective pressure p, vacuum and relative permittivity ε_0 and ε_r and the electric field E is very popular. It is used in various publications for estimating the potential of dielectric actuators, but also for detailed investigations [3,9,7,6,10,11].

Motivated by inconsistent experiments and finite element analyses, in 2007, Wissler et al. propose a new physical interpretation of Pelrine's equation (1), distinguishing "in-plane" and "out-of-plane" stresses [11]. Wissler compares measurement data to two-dimensional decoupled finite element simulations. They first evaluate the electric field distribution of a dielectric actuator in the cross section. Then, they calculate the two-dimensional mechanical pressure distribution resulting from the electric field. They find that Eq. (1) is correct in terms of absolute values. However, the force also has components in radial ("in-plane") direction.

Generally, the three dimensional behaviour of DEAs is covered by the Maxwell equations and the balance of momentum as shown by Dorfmann et al. [12]. The resulting coupled problem is rather complex and can be solved analytically only for special cases. In 2007, Vu et al. present a variational finite element formulation for the static coupled problem [13]. This model can be used to simulate the static state of arbitrary dielectric actuator geometries.

In order to control kinematic systems that are driven by dielectric elastomers, information about the time dependent behaviour of the actuators is required. Moreover, elaborate manufacturing methods result in complex inner structures of the elastomers [14]. Hence, three dimensional simulations with a fine resolution are necessary to cover all non-linear effects and to understand and control the functional principle of artificial muscles. At the same time, the derived model needs to be as simple as possible, since complex finite element simulations tend to be computationally very costly.

Building on the static finite element formulation introduced by Vu [13], in this work inertia terms are added in order to include time effects. It is assumed that electrodynamic effects take place on a considerably smaller time scale than elastodynamic effects. In order to reduce computational costs, magnetic interactions are not considered. The mathematical model describing the strong form of the coupled problem is introduced in Section 2. In Section 3, a corresponding variational setting is derived. The hyperelastic material model from Vu [13] is extended by viscoelastic terms that account for damping. The viscous stress tensor is based on a three dimensional form of the Kelvin–Voigt model proposed by Wriggers [15].

The variational setting allows for a structure preserving time integration [16]. Instead of discretising the vector based equations of motion, the discretisation is introduced into the scalar Lagrangian, as shown in Section 4. This procedure guarantees that important characteristics of the system are preserved exactly as illustrated in various works [17–19].

In Section 5, the derived finite element model is applied to various numerical examples. The influence of viscoelasticity is investigated and computational costs are evaluated. A dielectric actuator model with realistic geometry illustrates that even a macroscopic model is capable of resolving microscopic effects.